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2. Patent application number *(The Patent Office will fill in this part)* — 0320804.8

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Schlumberger Holdings Limited
P.O. Box 71
Craigmuir Chambers
Road Town
Tortola
British Virgin Islands

Patents ADP number *(if you know it)* — 7236326001

If the applicant is a corporate body, give the country/state of its incorporation — British Virgin Islands

4. Title of the invention

Borehole Telemetry System

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

William L. Wang
Intellectual Property Law Department
Schlumberger Cambridge Research Limited
High Cross
Madingley Road
Cambridge CB3 0EL
United Kingdom

Patents ADP number *(if you know it)* — ~~66350~~ 6633504003

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Claim(s)	4
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Date 4 September 2003

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William L. Wang
01223 325268

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DUPLICATE

BOREHOLE TELEMETRY SYSTEM

The present invention generally relates to an apparatus and a method for communicating parameters relating to down-hole conditions to the surface. More specifically, it pertains to such an apparatus and method for acoustic communication.

BACKGROUND OF THE INVENTION

One of the more difficult problems associated with any borehole is to communicate measured data between one or more locations down a borehole and the surface, or between down-hole locations themselves. For example, communication is desired by the oil industry to retrieve, at the surface, data generated down-hole during operations such as perforating, fracturing, and drill stem or well testing; and during production operations such as reservoir evaluation testing, pressure and temperature monitoring. Communication is also desired to transmit intelligence from the surface to down-hole tools or instruments to effect, control or modify operations or parameters.

Accurate and reliable down-hole communication is particularly important when complex data comprising a set of measurements or instructions is to be communicated, i.e., when more than a single measurement or a simple trigger signal has to be communicated. For the transmission of complex data it is often desirable to communicate encoded digital signals.

One approach which has been widely considered for borehole communication is to use a direct wire connection between the surface and the down-hole location(s). Communication then

can be made by wire-bound electrical signals. While much effort has been spent on "wireline" communication, its inherent high telemetry rate is not always needed and very often does not justify its high cost.

Another borehole communication technique that has been explored is the transmission of acoustic waves. Whereas in some cases the pipes and tubulars within the well can be used to transmit acoustic waves, commercially available systems utilize the various liquids within a borehole as the transmission medium.

Among those techniques that use liquids as medium are the well-established Measurement-While-Drilling or MWD techniques. A common element of the MWD and related methods is the use of a flowing medium, e.g., the drilling fluids pumped during the drilling operation. This requirement however prevents the use of MWD techniques in operations during which a flowing medium is not available.

In recognition of this limitation various systems of acoustic transmission in a liquid independent of movement have been put forward, for example in the US Pat. Nos. 3,659,259; 3,964,556; 5,283,768 or 6,442,105. However none of these techniques are successfully applied to monitor borehole parameters and transmit data to the surface during production enhancing operation such as fracturing.

It is therefore an object of the present invention to provide an acoustic communication system that overcomes the limitations of existing devices to allow the communication of data between a down-hole location and a surface location.

SUMMARY OF THE INVENTION

In accordance with a first aspect of the invention, there is provided an acoustic telemetry apparatus for communicating digital data from a down-hole location through a borehole to the surface or between locations within the borehole. The apparatus includes a receiver and a transmitter linked by an acoustic channel wherein the acoustic channel has a cross-sectional area of 58 cm^2 or less and the transmitter comprises an electro-active transducer generating a modulated continuous waveform.

The acoustic channel preferably provides a low loss liquid medium for pressure wave propagation between the transmitter and the receiver.

The use of active down-hole sources for the purpose transmitting measured data to a surface location has been hampered in the past by the fact that the amount of energy required to successfully operate the source is relatively large. In most case it exceeds the energy that can be stored in batteries, capacitors and the like to the extent that these sources are suitable for use in the harsh and spatially restricted environment of a typical subterranean hydrocarbon reservoir.

The power needed to generate a pressure wave of required amplitude is given by

[1] $$\Delta P=(\rho\ c^2)\Delta V/V$$

where ρ is the density of the acoustic medium and c the

speed of sound, V is the volume of the acoustic medium and ΔV is the variation of volume necessary to generate the pressure increment ΔP. Equation 1 means that for a large volume V, a large volume change ΔV is required to generate an appropriate pressure perturbation ΔP. In turn generating a large ΔV means that a large power source is needed. In cases where the liquid volume is large, i.e., when the whole annulus between a work string and the casing is used as the telemetry channel, the power drain on a down-hole source is considerable. For example for an annulus formed by a 7″ casing (0.16m inner diameter) and 3.5″ tubing (0.09m outer diameter), a 30Hz piston source with a displacement of 1mm (2mm peak-to-peak) can generate a wave amplitude of about 3 bar with an acoustic power of around 270W. Assuming a source efficiency of 0.5, then an electrical power of 540W is required down-hole. This makes a battery powered down-hole source generally impractical.

The present example therefore makes use of acoustic channels with a small volume and, hence, a small cross-sectional area. This approach is however difficult as the attenuation in a tubular acoustic medium depends partly on its radius:

$$[2] \qquad \alpha = (\mu\omega / (2\rho))^{0.5} / (c\ r)$$

where μ is the viscosity of the liquid, ω the angular frequency and r the inner radius of the tube. Given the wave frequency and the physical properties of the fluid, the tube radius r determines the signal attenuation. For communication through thin tubes, as proposed herein, the α value is large and the proper size of the tubes to be used

as an acoustic channel is a matter of careful consideration and selection to avoid total loss of the signal before it reaches the surface location.

The new system allows communication of encoded data that may contain the results of more than one or two different types of measurements, such as pressure and temperature.

The cross-sectional diameter of the acoustic channel is 58 cm^2 or less, corresponding to a 3 inch (7.5 cm) diameter. More preferably, the cross-sectional diameter of the acoustic channel is 25 cm^2 or less corresponding to a 2 inch (5.64 cm) diameter.

The acoustic channel used for the present invention is preferably a continuous liquid-filled channel. Often it is preferable to use a low-loss acoustic medium, thus excluding the usual borehole fluids that are often highly viscous. Preferable media include liquids with viscosity of less than 3×10^{-3} NS/m^2, such as water and light oils.

The acoustic channel may be implemented using a small-diameter continuous string of pipe, such as coiled tubing, lowered into the borehole prior to an intended well operation or, alternatively, by making use of permanently or quasi-permanently installed facilities such as hydraulic power lines.

In a preferred variant the apparatus may include an acoustic receiver at the down-hole location thus enabling a two-way communication.

The receiver of the telemetry system preferably includes signal processing means designed to filter the reflected wave signals or other noise from the upwards traveling modulated wave signals.

In a preferred embodiment the carrier waveform (the waveform before data modulation) is a single frequency sine wave or at least a narrow-band wave with 90% of the energy falling within boundaries defined by +/- 10 percent deviation from the nominal center frequency. The waveform is preferably a sinusoidal wave. The nominal frequency of the waveform may range from 0.1Hz to 100 Hz, depending upon the data rate requirement, the size of the liquid filled wave-guide tube, depth, and other parameters. For stimulation applications the frequency range may cover 1 to 100 Hz, preferably 1 to 10Hz.

The generator of the waveform is an efficient electro-mechanical or, more specifically an electro-dynamic transducer comprising electromagnetic coils or an electro-acoustic transducer or actuator comprising electro-active material, such as piezoelectric material, electro- or magneto-strictive material. The transducer may take the form of a stack of piezoelectric elements and may be combined with suitable mechanical amplifiers to increase the effective displacement of the actuator system.

In accordance with yet another aspect of the invention, there is provided a method of communicating digital data through a borehole employing the steps of establishing a column of liquid as acoustic channel through said borehole, said column having a cross-sectional area of 58 cm^2 or less;

generating at the down-hole location an acoustic wave carrier signal within said acoustic channel using an electro-active transducer; modulating amplitude and/or phase of said carrier wave in response to a digital signal; and detecting at the surface the modulated acoustic waves traveling within said acoustic channel.

In a preferred variant of the inventive method, the acoustic channel is established by lowering a liquid-filled coiled tubing string of the appropriate diameter of 3 inch or less, preferably 2.5 inch or less, or even 2 inch or less into the borehole.

Further aspects of the invention include the use of the above apparatus and methods in a well stimulation operation, such as fracturing or acidizing.

These and other aspects of the invention will be apparent from the following detailed description of non-limitative examples and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGs. 1A,B illustrate elements of an acoustic telemetry system in accordance with an example of the invention using coiled tubing as acoustic channel;

Fig. 2 shows elements of an alternative embodiment of the novel telemetry system using a hydraulic power line as acoustic channel;

FIGs. 3A,B show simulated signal power and power loss spectra: and

FIG. 4 is a flows diagram illustrating steps of a well stimulation method in accordance with the invention.

EXAMPLES

A first example of the invention is shown in FIG.1A which depicts an example of the novel telemetry system in a well **100** during a well stimulation operation.

Prior to performing the stimulation, a down-hole measurement and telemetry sub **120** is mounted on a coiled tubing **110** to be positioned below perforations **101**.

Coiled tubing system **110** includes a tubing reel **111** and a tubing feeder **112**, which is mounted on a support frame **113**. Feeder **112** pushes the tubing into well **100** through a well head **102**, which is part of the surface installation. The surface end of coiled tubing **110** is connected to a liquid pump **114** through an instrumented pipe section **113**, on which a number of pressure/acoustic transducers **115**, **116** are mounted.

Down-hole measurement and telemetry sub **120** which is shown in more detail in FIG. 1B includes a measurement unit **121** with various sensors **122** for recording down-hole pressure and temperature. It further includes a power supply unit **123** with batteries to provide power to the operation of the sub and further electronic circuits to condition and digitize any analog signal. A power modulator **124** encodes measured data into a modulated voltage signal carrying the digitized data for driving a pressure/acoustic wave source **130** through a cable **125**.

Source **130** is an electro-mechanical transducer that converts an electrical driving power (voltage or current) into a mechanical displacement. It includes a piezoelectric stack **131** protected by a housing **132**, an inner flow-through tube **133**, pressure transparent membrane **134** and protection fluid (electrically insulating) **135**.

The liquid flow through sub **120** is controlled by two valves **125**, **126** and the associated driving systems **127, 128**. Valve **125** is a sliding or rotating sleeve valve, which is installed above source **130**. Its driving unit **127** is linked to electronics/sensor unit **121**. Valve **126** is shown to be a full bore solenoid flow-through valve, which is installed below the sub.

Valves **125**, **126** are operated so as to enable pumping cleaning fluid through coiled tubing **110** to clean up unwanted materials such as proppants after a stimulation operation. Additionally, valves **125**, **126** facilitate filling up and pressurizing coiled tubing **110** with liquid, so that the attenuating effect of air trapped in the tubing is minimized and the channel established by the liquid in coiled tubing **110** is suitable for acoustic wave transmission.

Before a stimulation, liquid pump **114** pumps a low viscosity fluid such as water through coiled tubing **110** to fill it up, and pressurizing it to an appropriate pressure by continuing pumping after closing the down-hole valve **126**.

During the stimulation operation, the stimulation fluid is

pumped into the cased well bore **100** from a well head entry **103**. The fluids flow into the formation through the perforations **101** above measurement/telemetry sub **120** deployed by coiled tubing **110**. A blast joint (not shown) is mounted where the stimulation fluid first meets the coiled tubing to protect the coiled tubing from erosion. The down-hole measurement/telemetry sub **120** starts to record pressure, temperature and other data after the stimulation process begins. The data is then converted to a binary code, which modulates a sinusoidal or pulse voltage with one or a combination of the following modulation schemes: frequency shift keying (FSK), phase shift keying (PSK), amplitude shift keying (ASK) or various pulse modulation methods, e.g. pulse width or pulse position modulation.

In the example, modulation of sinusoidal waves with a digital method such as FSK or PSK is used. The modulated electrical signal is converted to a pressure/acoustic wave of same modulation by the down-hole electro-mechanical source **130**.

The wave is detected by at least one, or more, pressure/acoustic transducers **115, 116** on the surface. The transducers are spatially separated by more than 1/8 of wavelength of the carrier wave. The spatial separation allows to apply various known techniques to improve the reception of the signal in the presence of noise and interference as caused for example by reflected waves.

The telemetry system shown in FIG. 1 can be made bi-directional by installing a pressure/acoustic transducer in the down-hole sub, and a pressure/acoustic wave source on

surface.

The sensing element of the down-hole transducer is exposed only to the liquid inside the coiled tubing, and therefore insensitive to the stimulation pressure outside the tubing. The surface source can be built similar to the design of the down-hole source, however the power required to operate it can be supplied from an external source.

To perform a surface to down-hole down communication, the surface source sends out a signal in a frequency band that is outside the frequency band of the upward telemetry. Therefore the two-way communication can be performed simultaneously without interfering with each other. A bi-directional telemetry system is relevant if during the operation, the operational modes of down-hole devices, such as sampling rate, telemetry data rate, are to be altered. Other functions unrelated to altering measurement and telemetry modes may include opening or closing certain down-hole valves or enable/disable the down-hole source.

Alternatively to the deployment on a coiled tubing the communication system of the present invention may be used in conjunction with hydraulic control lines. Modern wells are often completed with production tubing, down-hole sensors for permanent monitoring and down-hole control devices such as valves. In such completions often at least one hydraulic control line is deployed with the production tubing. Provided the line has a diameter that renders it useful for the application of the invention, e.g. with a 1/4 inch (nominal size of the inner diameter) diameter tubes, it can provide a channel for pressure signal communication between

a down-hole transmitter and a surface controller.

In normal practice of so-called "intelligent" completion, electrical cables are used to provide the communication link between any down-hole sensors and surface data acquisition system. The cables also provide electrical power to the down-hole sensors. However as the installation of cables and pipes alongside the production tubing is difficult, a telemetry system based on a hydraulic line, as proposed herein, can be advantageous as it alleviates the need to install additional electrical cables.

FIG. 2 shows an arrangement of a system utilizing a permanently installed hydraulic control line as an acoustic telemetry channel for monitoring down-hole parameters of a producing well **200**. FIG 2 illustrates schematically the side wall of well **200** along which a hydraulic line **210** linking a surface hydraulic controller **211** to a down-hole valve **220**. To enable hydraulic pressure transmission , line **210** is filled with a hydraulic liquid.

Operation commands, in the form of pressure signals, are generated on surface by controller **211** and transmitted to down-hole actuator/valve **220** via hydraulic control line **210**. Control line **210** can normally be deployed through various sealing devices in the annulus **201** between production tubing **202** and casing **203**. The sealing devices may include a surface seal **204** and a number of down-hole packers **205**.

Whereas the above-described parts of the installation are known per se, it is seen as a feature of this example of the invention that control line **210** is made hydraulically

accessible to a pressure wave source **230** based on an electro-mechanical device, such as a piston driven by a piezoelectric stack. In the present example, hydraulic access is provided by a T-type pipe joint **212**. Pressure source **230** is connected to a down-hole telemetry unit **231** via a cable **232**. Measurement data from various down-hole sensors **233** can be sent to telemetry unit **231** via multiple cables (electrical or optical), or via a single cable that serves as a data bus. Telemetry unit **231** encodes the data and provides a carrier signal wave with the appropriate modulation for transmission of the digital data, e.g. binary frequency or phase modulation. The unit **231** also provides power amplification to the modulated signal before the amplified signal is then applied to pressure wave source **230**. The data-carrying pressure wave propagates through the liquid in hydraulic line **210** to the surface. One or more pressure transducers **213, 214** mounted on hydraulic line **210** detect the modulated carrier wave on the surface. A surface signal processor or demodulator **215** receives the pressure signals from transducers **213, 214** and demodulates them to recover the transmitted data.

As in the previous example, the down-hole sensors and electronics for measurement and telemetry can be battery powered. However in a permanent down-hole installation, the life span of a down-hole battery may not be sufficient for long term monitoring applications. In a variant of this example it is therefore proposed to generate electric power down-hole by using pressure waves generated on surface.

As shown in FIG. 2, a pressure wave source **216**, which may be a piezoelectric piston source driven by a sinusoidal wave

generated in an electrical power supply **217**, is mounted on the surface section of the hydraulic control line via a T-type pipe junction **218**. This source can generate pressure wave at frequencies higher that those generated by hydraulic controller **211**. Several hundred Watts of acoustic power may be generated by surface source **216**. Even after taking into consideration a propagation attenuation of several dB/kft, there will be 1-10 Watts acoustic power available down-hole at the end of a, for example, 10kft or 3300 meter borehole. This acoustic power can be converted to electrical power by a piezoelectric converter **222**, mounted on a down-hole section of hydraulic control line **210** via a T junction **219**. The converted electrical current flows into an energy storage unit **223** via a cable **224**. Storage unit **223**, which may be a capacitor bank, supplies electrical power to the down-hole sensors and to the telemetry unit **231**.

In a typical permanent monitoring operation, the frequency at which down-hole data are acquired and transmitted is low, amounting to the transmission of a batch of data once or twice per hour. Therefore energy accumulated during the long idle intervals should be sufficient to power the down-hole devices during the infrequent active intervals. Operations exists for which a single down-hole pressure source **230** is sufficient for use as both, data transmitter to transmit measured data to the surface and electrical power converter for the acoustic power sent from surface.

The configuration of FIG. 2 also facilitates a two-way telemetry system. In a two-way telemetry set-up surface source **216** is used to send down-link commands, in the form of digitally coded pressure waves, to down-hole devices, in

order to change their operation modes. Either single down-hole pressure source **230** or, alternatively, piezoelectric converter **222** may be used as down-hole receiving transducers. Appropriate signal-processing/demodulation functions can be built into down-hole telemetry unit **231** to decode the commands.

To avoid cross-interferences between the hydraulic control system, the up-link telemetry system, the down-link telemetry system and the power generation system, wave frequencies are separated. For instance, the frequency of the hydraulic control signal may be below 0.5 Hz, the up-link telemetry frequency may be between 1 Hz to 3 Hz, the down-link telemetry band may occupy the next frequency band from 3 to 5 Hz and the power generation frequency may be around 7Hz. If these different systems can be operated at different time intervals, they may time-share a one or more common frequency band.

In FIGs. 3 A, B, there is shown a simulated example to illustrate the working of the new telemetry system through thin tubes.

FIG. 3A shows the simulated amplitude versus source frequency for a peak-to-peak displacement of 0.3 mm generated by a piston of 2.5 inch diameter generating pressure waves in a water filled tube. The upper solid curve **301** represents the case of a 1 inch inner diameter tube and the lower dashed curve **302** represents a 2-inch tube. The amplitude is measured in Pa and the frequency in Hz. The amplitude in the larger tube is significantly lower. The acoustic power produced by such a system is around 2W at

30Hz. Assuming a source efficiency of 0.25, the electrical power required to generate the wave signal is less than 10W, and, hence, within the limits of the amount of power that can be stored or generated at a down-hole location.

FIG. 3B shows the simulated attenuation coefficients in decibels (dB) per 1000 ft versus frequency for coiled tubing with 1-inch (solid curve **303**) and 2-inch (dashed curve **304**) inner diameters. As the diameter decreases the attenuation increases leading to a higher attenuation in the 1-inch tubing. However with a wave amplitude of 30psi is generated at 25Hz in a 1″ tubing, a loss of 15dB over a depth of 10000 feet would provide more than 5psi signal amplitude on surface.

The attenuation can be high for very thin tubes such as a ½-inch hydraulic control line (3mm inner diameter). However, for a low data rate application in a low noise environment, such as well monitoring, a very low frequency at around 1-5 Hz may be used to reduce attenuation. Since the tube is thin, high signal amplitude can be generated even at low frequencies (as demonstrated in FIG. 3A), thus sufficient signal to noise ratio can be achieved on the surface.

The above apparatus and method is particularly advantageous when applied to a well stimulation operation such as acidizing or fracturing. For these operations it is often desirable to have a flexible and readily deployable method of measuring data at a predetermined location in the well and transmitting the measured data to a surface location.

If for example an existing well requires stimulation, the operation can be started as illustrated by FIG. 5 by first lowering from the surface a small-diameter coiled tubing with the measurement and telemetry sub as described in FIG. 1. When the sub reaches the target depth, an acoustic channel is established in step **41** by filling the coiled tubing with water or any other low-loss liquid. The acoustic source is activated in the following step **42** and measured data such as temperature and pressure are encoded and transmitted as a modulated wave signal to the surface receivers where it is demodulated and filtered to recover the original data (step **43**).

In a fracturing operation the operator can then start pumping the fracturing fluids and proppants as required from the surface (step **44**). It will be appreciated that the acoustic channel through the coiled tubing is not affected by the stimulation operation and can continue to be used as telemetry system to monitor the down-hole conditions during the whole and after completing the stimulation (step **45**).

In a final step of the operation the coiled tubing is retrieved.

While the invention has been described in conjunction with the exemplary embodiments described above, many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure. Accordingly, the exemplary embodiments of the invention set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.

CLAIMS

1. An acoustic telemetry apparatus for communicating digital data from a down-hole location through a borehole to the surface or between locations within the borehole, said apparatus comprising a receiver and a transmitter separated by an acoustic channel wherein the acoustic channel has a cross-sectional area of 58 cm^2 or less and the transmitter comprises an electro-active transducer generating a modulated continuous waveform.

2. The acoustic telemetry apparatus of claim 1 wherein the waveform is modulated to transmit the data.

3. The acoustic telemetry apparatus of claim 1 the waveform is modulated to transmit encoded data comprising the results of more than one or two different types of measurements.

4. The acoustic telemetry apparatus of claim 1 wherein the cross-sectional diameter of the acoustic channel is 25 cm^2 or less.

5. The acoustic telemetry apparatus of claim 1 wherein the acoustic channel is a column of liquid extending from the surface to a down-hole location.

6. The acoustic telemetry apparatus of claim 5 wherein the acoustic channel is a continuous liquid-filled tubing string temporarily suspended in the borehole.

7. The apparatus of claim 5 wherein the acoustic

channel is a tubular control line permanently or quasi-permanently installed in the borehole.

8. The apparatus of claim 7 wherein the acoustic channel is a tubular control line permanently or quasi-permanently installed in the well bore providing simultaneously hydraulic control to a down-hole installation.

9. The acoustic telemetry apparatus of claim 5 wherein the column of liquid has a viscosity of less than 3×10^{-3} NS/m^2.

10. The acoustic telemetry apparatus of claim 1 further comprising an acoustic source installed at the surface and a receiver installed at the down-hole location to enable two-way communication through the acoustic channel.

11. The acoustic telemetry apparatus of claim 1 further comprising a signal processing device adapted to filter the reflected wave signals or other noise from the upwards traveling modulated wave signals.

12. The acoustic telemetry apparatus of claim 1 wherein the waveform has narrow-band of less than +/- 10 percent half-width deviation from a nominal frequency.

13. The acoustic telemetry apparatus of claim 1 wherein the waveform is preferable a sinusoidal wave.

14. The acoustic telemetry apparatus of claim 1 wherein the transducer comprises piezo-electric material.

15. Use of the apparatus of claim 1 in a well stimulation operation.

16. A method of communicating digital data from a down-hole location through a borehole to the surface comprising the steps of:

establishing a column of liquid as acoustic channel through said borehole, said column having a cross-sectional area of 58 cm^2 or less;

generating at the down-hole location an acoustic wave carrier signal within said acoustic channel using an electro-active transducer;

modulating amplitude and/or phase of said carrier wave in response to a digital signal; and

detecting at the surface the modulated acoustic waves traveling within said acoustic channel.

17. The method of claim 16 further comprising the steps of performing measurements of down-hole parameters, encoding said measurements into a bitstream; and controlling the transducer in response to said encoded bitstream.

18. The method of claim 16 further comprising the step of selecting the frequency of the carrier wave in the range of 0.1 to 100Hz.

19. A method of stimulating a wellbore comprising the steps of

performing operations designed to improve the production of said wellbore while simultaneously establishing from the surface to a down-hole location a column of liquid as acoustic channel through said borehole;

generating at the down-hole location an acoustic wave carrier signal within said acoustic channel using an electro-active transducer;

modulating amplitude and/or phase of said carrier wave in response to a digital signal; and

detecting at the surface the modulated acoustic waves traveling within said acoustic channel..

20. The method of claim 19 wherein the step of establishing from the surface to a down-hole location a column of liquid as acoustic channel comprises the step of lowering a small-diameter coiled tubing string into the borehole

ABSTRACT

An acoustic telemetry apparatus and methods for communicating digital data from a down-hole location through a borehole to the surface or between locations within the borehole are described including a receiver and a transmitter linked by an acoustic channel wherein acoustic channel has a cross-sectional area of 58 cm^2 or less and the transmitter comprises an electro-active transducer generating a modulated continuous waveform.

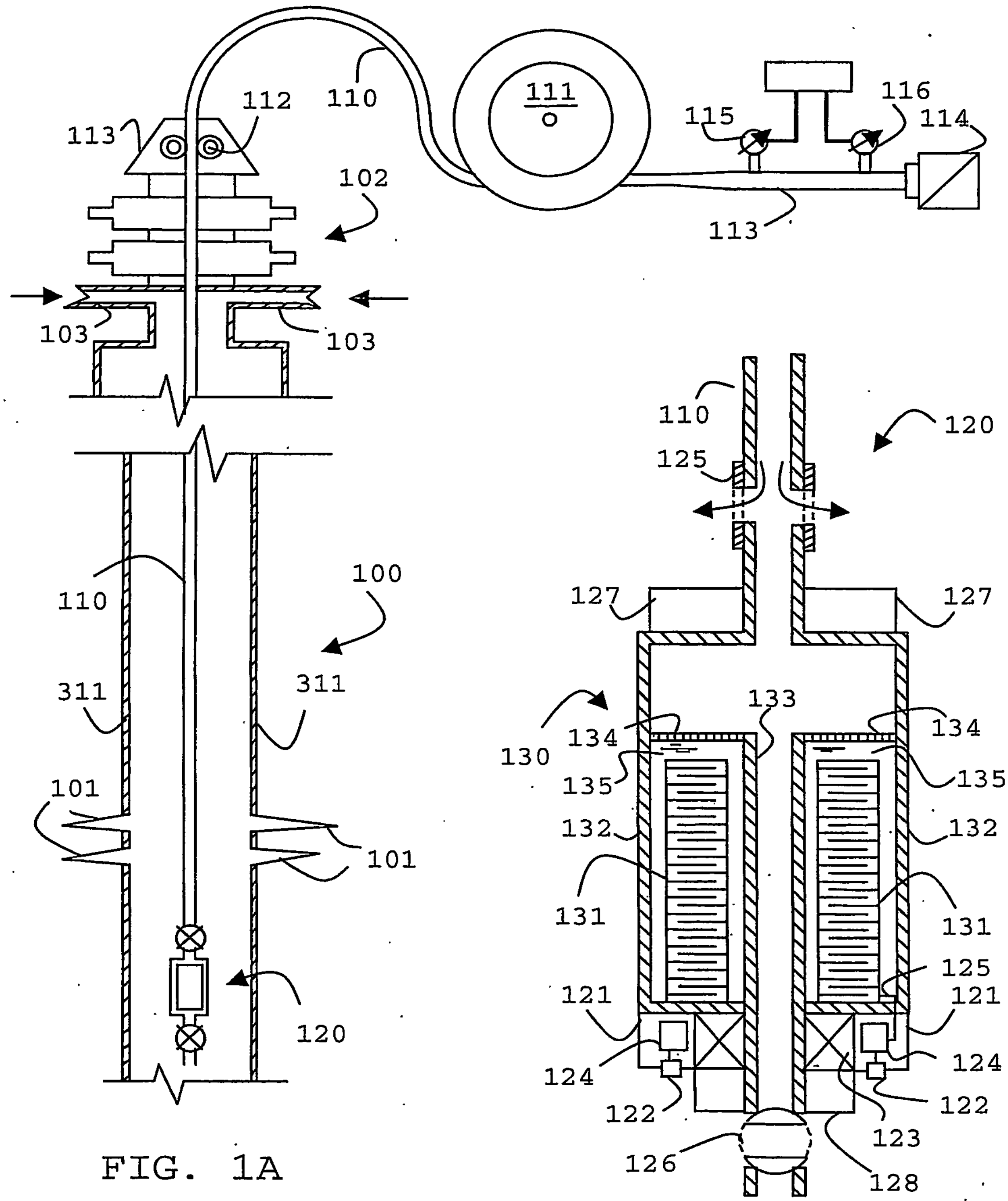
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FIG. 1A

FIG. 1B

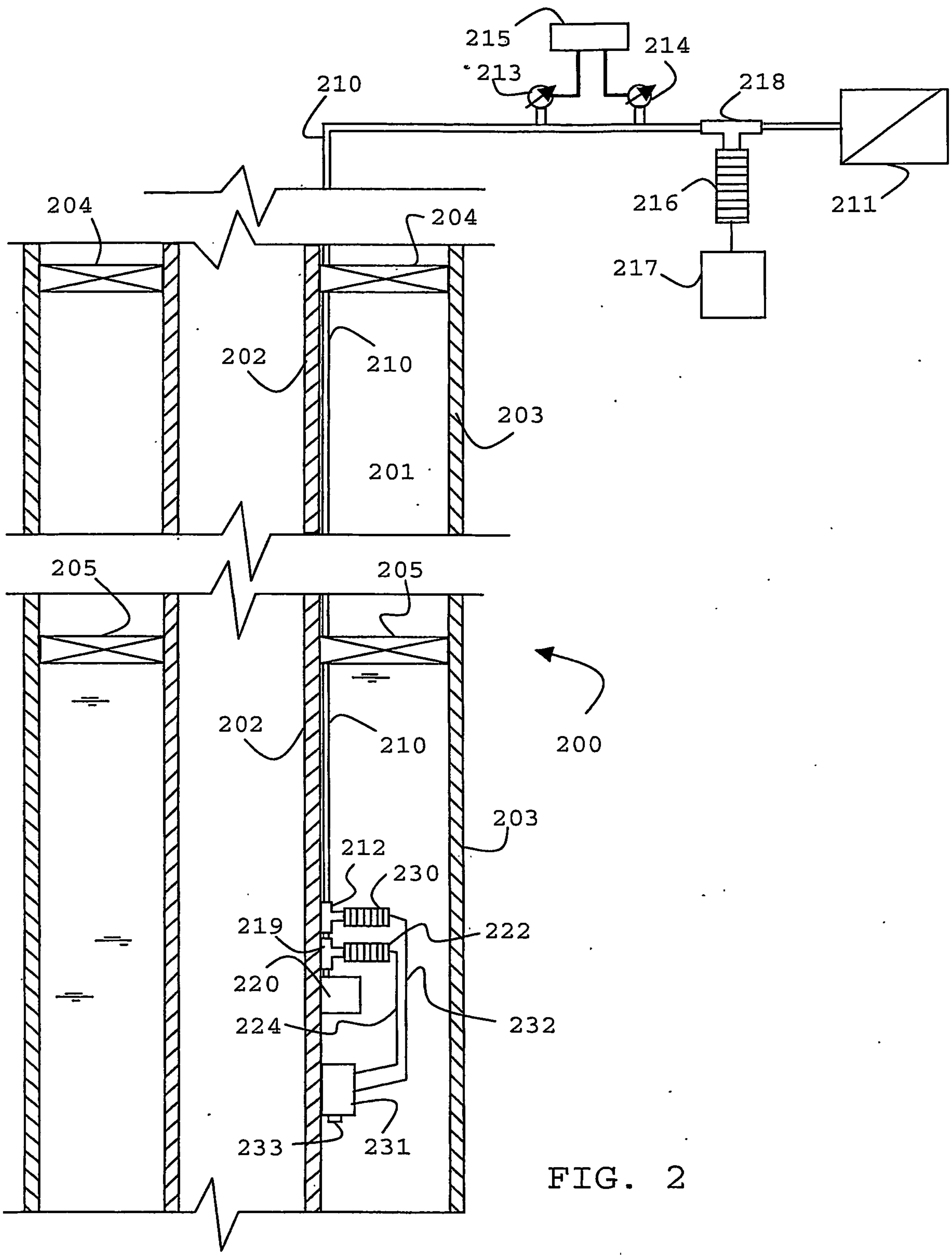
215
214
213
210
218
211
216
217
204
204
202
210
203
201
205
205
202
210
200
203
212
230
219
222
220
224
232
233
231

FIG. 2

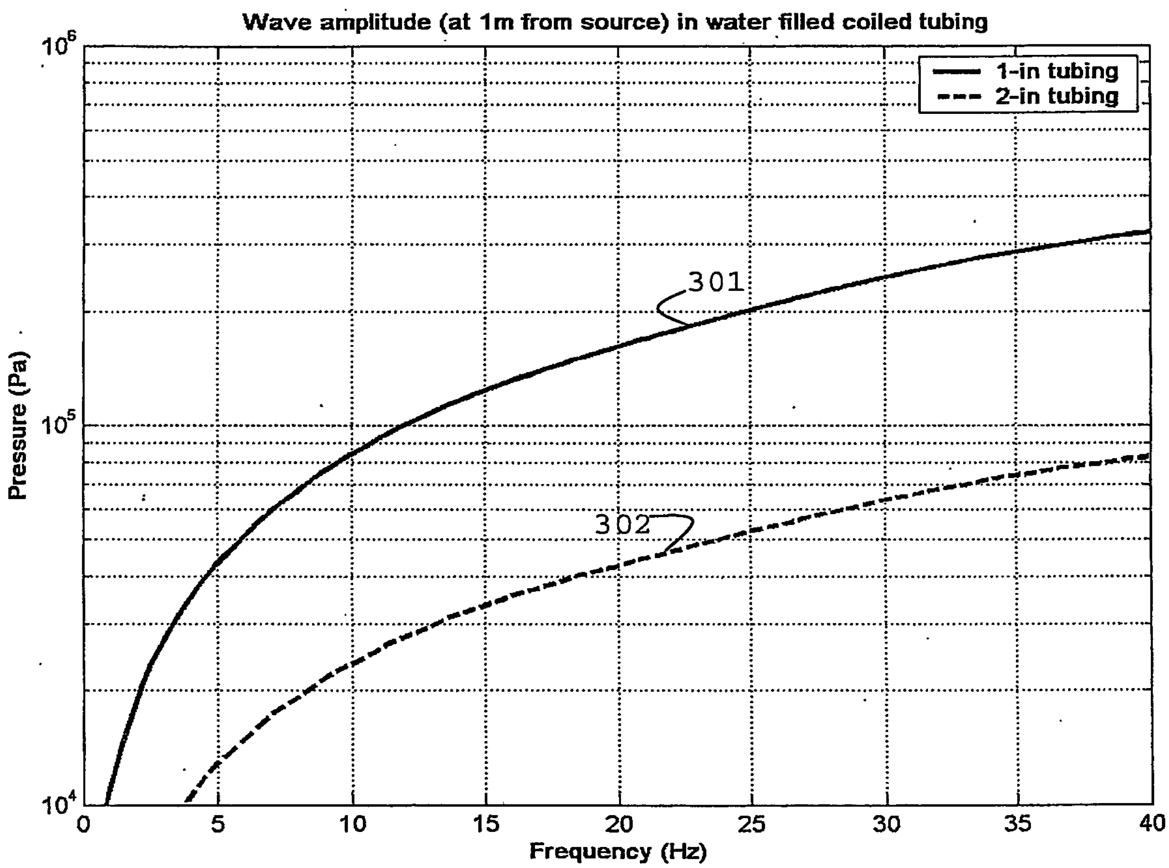
Wave amplitude (at 1m from source) in water filled coiled tubing
10^6
10^5
10^4
Pressure (Pa)
0
5
10
15
20
25
30
35
40
Frequency (Hz)
1-in tubing
2-in tubing
301
302

FIG. 3A

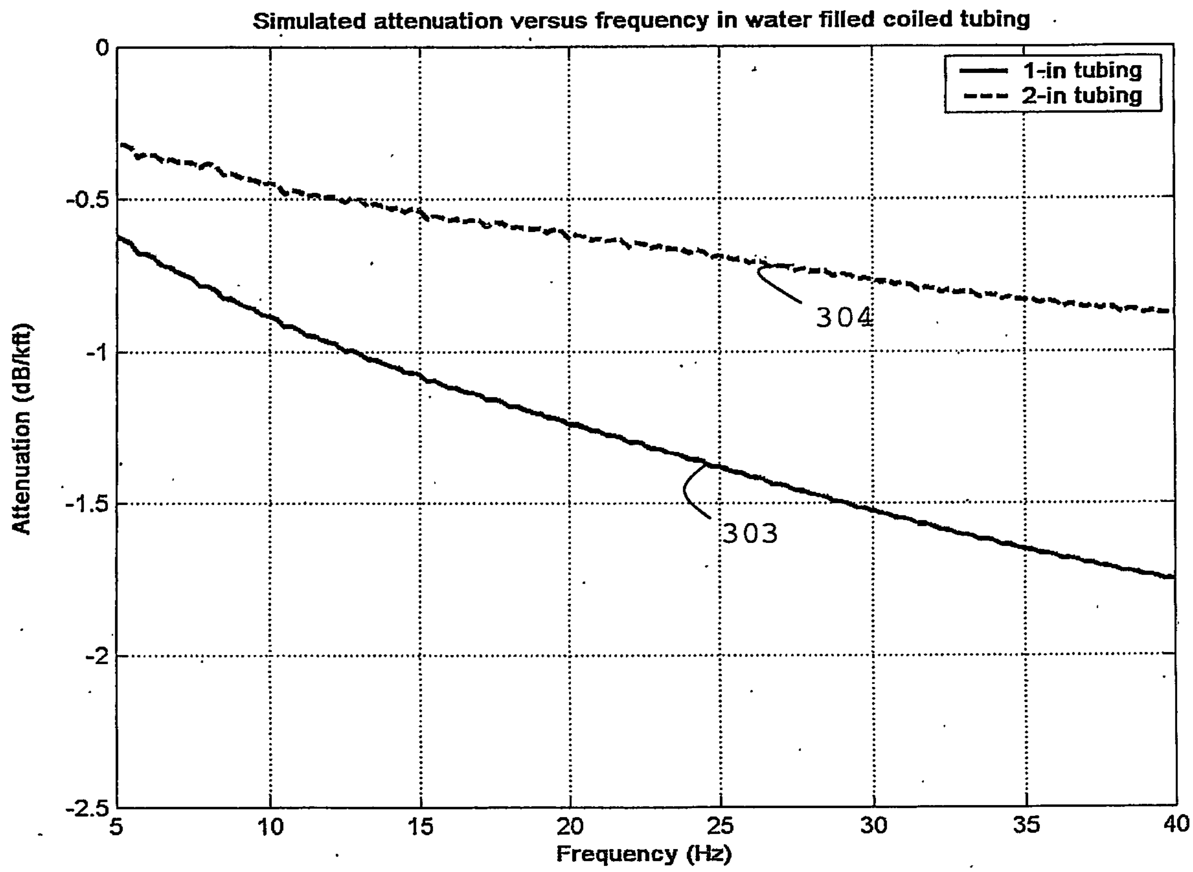
Simulated attenuation versus frequency in water filled coiled tubing
1-in tubing
2-in tubing
Attenuation (dB/kft)
Frequency (Hz)
0
-0.5
-1
-1.5
-2
-2.5
5
10
15
20
25
30
35
40
304
303

FIG. 3B

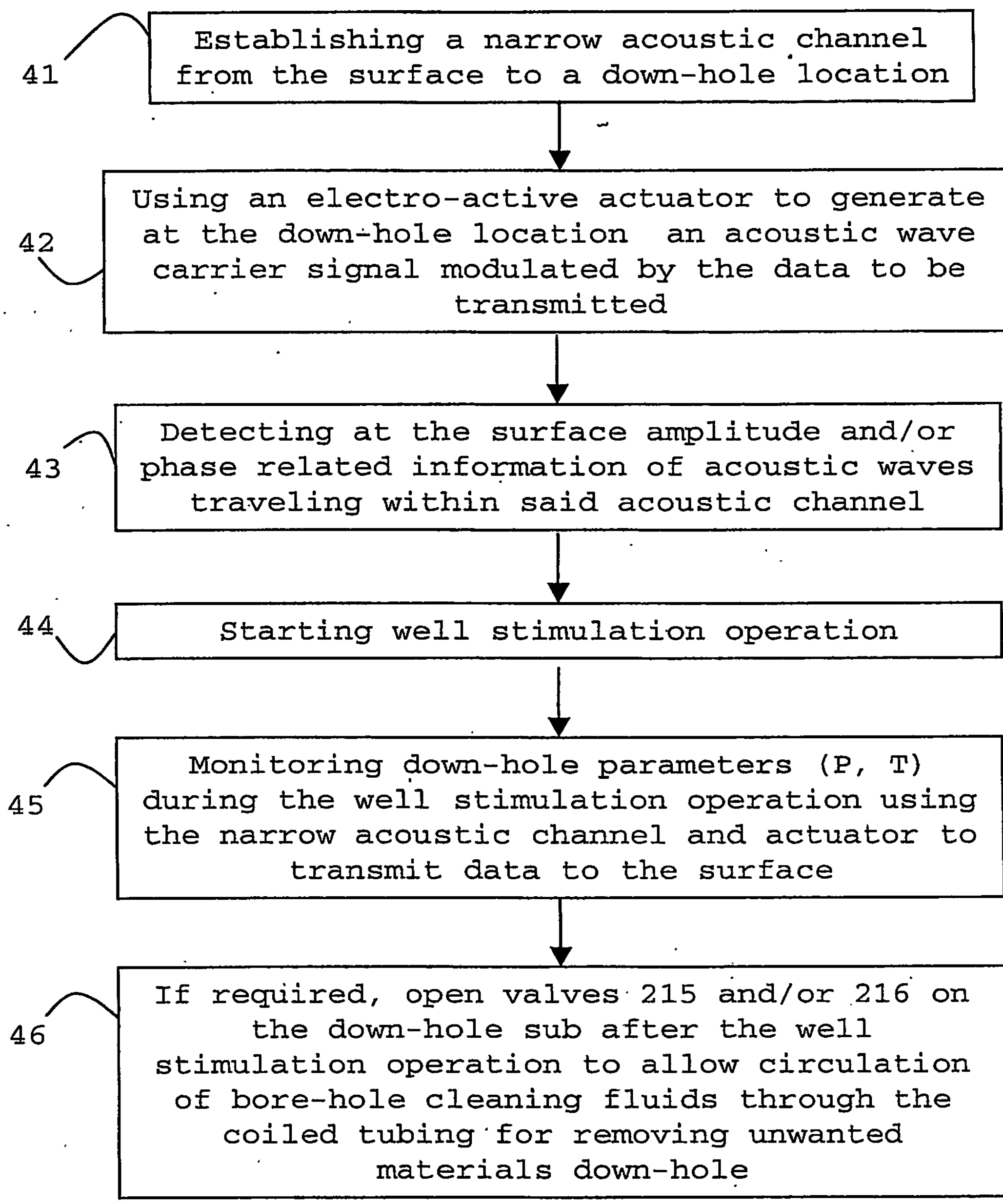
41
Establishing a narrow acoustic channel from the surface to a down-hole location
42
Using an electro-active actuator to generate at the down-hole location an acoustic wave carrier signal modulated by the data to be transmitted
43
Detecting at the surface amplitude and/or phase related information of acoustic waves traveling within said acoustic channel
44
Starting well stimulation operation
45
Monitoring down-hole parameters (P, T) during the well stimulation operation using the narrow acoustic channel and actuator to transmit data to the surface
46
If required, open valves 215 and/or 216 on the down-hole sub after the well stimulation operation to allow circulation of bore-hole cleaning fluids through the coiled tubing for removing unwanted materials down-hole

FIG. 4